

CARBON DYNAMICS: EVER GOING TO STOP INCREASING?

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Abstract

The purpose of the study was to mimic carbon dynamics in the atmosphere and to simulate the change of carbon under different versions of the base model. The simulation contains namely three stocks the CO₂ in atmosphere, - in biosphere and - emission from fossil fuels. The assumption is that ocean carbon uptake and outflow cannot be directly influenced by policy makers. There are factors influencing carbon in- and outflow which are the rate of respiration, the decomposition, the area of forests, the net primary production, the deforestation, the assumed growth rate of fossil fuel demand and the saturation of consumption. The study unveils the dynamic of this process by applying system thinking and uses AnyLogic 6.9.0 version software for modeling system dynamics. The model originally elaborated by Hartmut (1994). The software facilitates to forecast the change of carbon if fossil fuel consumption will saturate and if deforestation will be stopped. The overall aim was to create a simulation to see the sensitivity of the ecosystem and try to eliminate climate change due to the escalation of carbon. The results of this analysis can be used to identify the necessary changes to stop carbon growth in the atmosphere. The anticipated outcome of this simulation is to set up the original model and to create three versions of the base model. The findings may be useful for decision makers in the field of sustainability, biomass power plants operators or for energy and environment strategy managers.

Keywords: Carbon dynamic, system thinking, atmosphere, biosphere, fossil fuel, model ecosystem, deforestation

Introduction

Carbon dioxide is considered to be the most relevant influential factor for global warming and climate change which resulted from human activities. The concentration of carbon dioxide in the atmosphere is rapidly increasing year by year, past year average increase was 2 ppm/yr (parts per million per year). Currently the CO₂ level was 395.15 ppm in august 2013 (NOAA, 2013; Scripps Institution of Oceanography, 2013). If the growth dynamic do not change or develop more dynamically, the world is going to face serious consequences as 50 million years back when the earth was ice-free until the CO₂ level dropped below 450 ppm. The safety limit of the carbon concentration in the atmosphere is 350 ppm. If we exceed the level 450-500 ppm that would induce significant stress on our biodiversity, lead to the extinction of several species, global warming, change the global ecosystem and increase the number of natural hazards. Unfortunately 350 ppm was already exceeded in the year of 1988 (Hansen et al. 2008, Pacauri, Reisinger, 2007). The process is only reversible by prompt policy changes.

It has been proved that the increase of carbon dioxide in the atmosphere was in the same speed with the combustion and use of fossil fuel energies starting from the industrialization. Also the beginning of the industrial sized deforestation in 1970 has

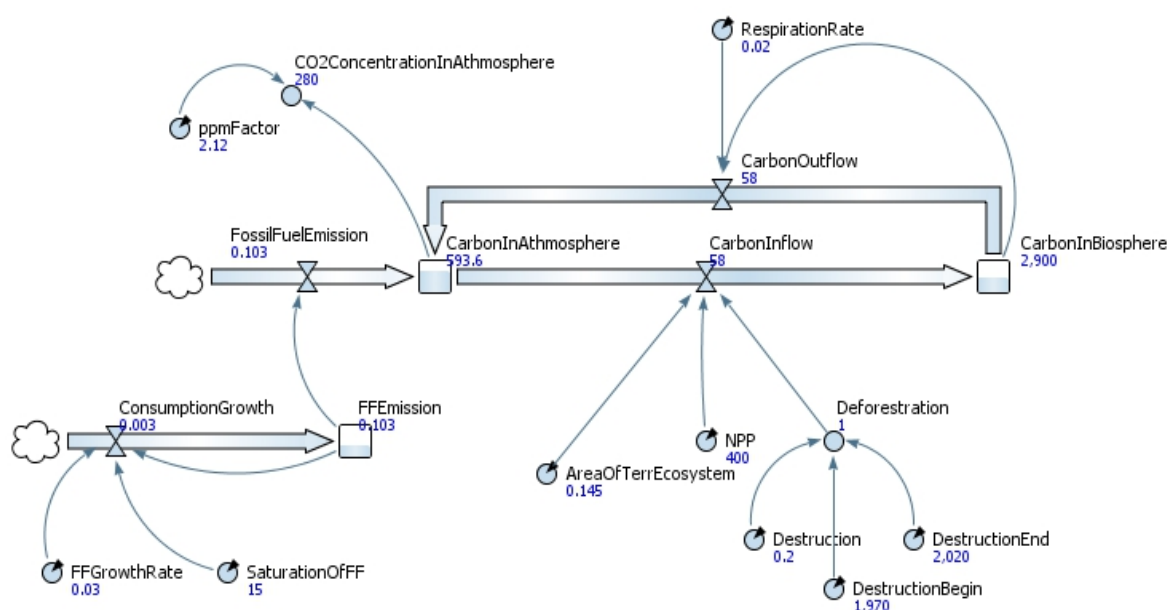
triggered the increased carbon dioxide concentration in the air. Forest is one of the largest carbon sink, along with the atmosphere and ocean. Any change or disruption in the system will reduce the size of the carbon sinks. Consequently if the use of traditional source of energies and deforestation is not going to be eliminated, then the options for mitigating probable climate change is limited (Hartmut, 2007, le Quéré et al, 2009; Canadell, 2007).

Before policy making one should understand that ecosystem is a highly complex system where each individual part is in relation with the whole complexity. It is not possible to change an element without measuring its impact and observe its consequences. A system is defined by Meadows (2008, p188) as “an interconnected set of elements that is coherently organized in a way that achieves something (function or purpose)”. A behavior of a system can be predicted by knowing the elements of the system. Interconnection between each element is responsible to supply the necessary information which is determined by the general function of the system. Function is a higher level state which has a dramatic affect when being modified. Therefore model creation facilitates the process to observe system behavior over time with the help of graphs. Modeling system behavior will help us understand whether the system is approaching a goal or a limit, and see the dynamic of the process (Meadows, 2008).

The first section is going to guide the reader through the verbal model that is going to explain the details and content of the base model including parameters and applied data. The second section is introducing three different versions of the base model and interpreting the findings. The third section will follow with recommendations from an economic prospective and see the financial consequences of the current.

Description of the model

Hartmut (1994 p346, 2007) findings have provided the basis for our simulation. In the original model the author was trying to model the CO₂ dynamics in the atmosphere after 1850 when the equilibrium state was being disturbed. The added value beyond regenerating Hartmut model is to extend it with different versions assuming optimistic and pessimistic situations by modifying or adding new parameters and find an ideal path to stabilize carbon dioxide concentration. During model development AnyLogic software was used which required the exact definition of equations and data. Hence a thorough and critical review of the base model had to be conducted.



1. Figure Base model interpreting carbon dynamics at the first stage of model development (*the figure is made by the author*)

The model contains two main carbon stocks. Namely one stock represents carbon level in the atmosphere and the other stock represents the carbon in biosphere (See Figure 1). These two stocks are interrelated, both are influencing one another. There will be parameters effecting and determining this relation, so called the flow of carbon uptake and intake. It is known that humanity's carbon dioxide is being sequestered by three sinks: the atmosphere (50%), the biosphere (26%) and the ocean (24%) (le Quéré, 2009, Hall, 1988). The original model made by Hartmut (1994) has neglected carbon intake by the ocean to simplify the model and he assumed it is a relatively small amount. The model will disregard ocean as a carbon sink at this stage of the model development. The assumption is that ocean carbon uptake and outflow cannot be directly influenced by policy makers, therefore a simplified model will be used now since at other carbon sinks there are more tools to influence carbon sequestration. Furthermore the next research question of the author will be to model the change in carbon uptake particularly of forest and crop land under different agro-strategies proving that biomass plants are not carbon neutral. Le Quéré (2009) and Canadell (2007) have found that the carbon sinks sequestration capacity is deteriorating due to the negative response to climate change and variability. Between 1959 and 2008 there were 43% more carbon remaining in the air than before (le Quéré, 2007). The ocean pH content before the industrialization was 8.179 and currently it is 8.104. It has decreased by 0.075 which results in the acidification of oceans and if pH level reaches 7.824 as a prognosis said by 2100, it will danger the existence of coral reefs and alters the ecosystem of the ocean (Caldeira, Wickett, 2003; Raven et al, 2005). If the acceleration of carbon in atmosphere would stop, that would consequently solve the acidification of the ocean. The carbon in biosphere at the equilibrium state (before industrialization) was 2,900 ppm which is being determined by the total terrestrial area of the ecosystem, 0.145 Gkm^2 (giga km^2) and the net primary production which is 400 Gt C (gigaton of carbon) showing the amount of net carbon dioxide taken in by plants minus the respiration (McGraw-Hill, 1982). This equation was disturbed by deforestation starting in 1970 and the assumption of the base model is that it will be stopped in 2020. It is changing with a rate of 0.02% per year. This parameter has a negative feedback loop for the system. It has explained the carbon tied in the biosphere through photosynthesis. The carbon outflow from biosphere occurs during the respiration of the ecosystem (plants, animals), and the decomposition of organic matters. It is estimated on a rate of 0.02 per year. It is depending on the rate of carbon in the biosphere, consequently there is a link between the flow and the stock. The following equation expresses the carbon in biosphere in relation of time.

Carbon in Biosphere/dt

$$= \text{Area of Ecosystem} * \text{NPP} * \text{Deforestation} - \text{Respiration rate} * \text{Carbon in Biosphere}$$

The other large stock is carbon in atmosphere. There is one carbon outflow, the sequestration of biosphere and there are two carbon inflows: carbon from respiration, decomposition and carbon from the combustion of fossil fuels. The historical CO₂ equilibrium was 280 ppm in the atmosphere until 1850, when burning fossil fuel overbalanced the equilibrium state (Hydrogen, 2002). If rate of burning coal, oil, and natural gas would be less intensive; the CO₂ concentration may not change so dramatically in the air. The following equation expresses the carbon in atmosphere in relation of time.

Carbon in Atmosphere/dt

$$= \text{Fossil fuel emission} + \text{Respiration rate} * \text{Carbon in Biosphere} - \text{Area of Ecosystem} * \text{NPP} * \text{Deforestation}$$

There is an auxiliary, so called CO₂ concentration in atmosphere, which is starting from the carbon in atmosphere stock with the purpose merely to express carbon in the air in ppm. It is calculated so that the carbon in the atmosphere is divided by 2.12 Gt C/CO₂ppm.

The last complex dynamic subsystem describes the carbon emission of fossil fuel during combustion. It assumes a 0.1 Gt carbon emission per year and calculates with a 0.03% growth per year. The model hypothetically defines saturation in fossil fuel consumption at a rate of 15 Gt C per year. The expectation is that it will result in a logistic curve at the fossil fuel emission stock, where the function starts at a given rate, while growing up until a certain rate and will stay unchanged. This dynamic system is going to influence the atmosphere. The following equation expresses the carbon in atmosphere in relation of time.

$$\begin{aligned} \text{Carbon emission of FossilFuel}/dt &= \text{Fossil Fuel growth rate} * \text{Fossil fuel emission} * (1 \\ &\quad - \frac{\text{Fossil fuel emission}}{\text{saturation in consumption}}) \end{aligned}$$

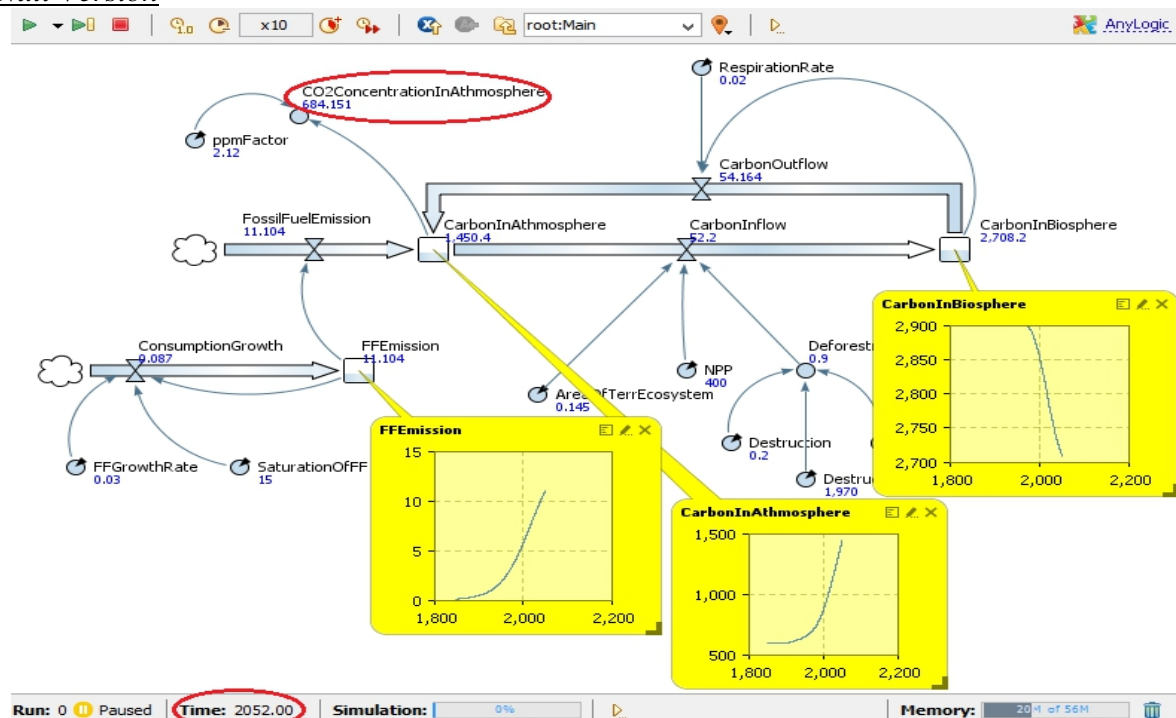
According to Le Quéré (2009) and Canadell (2007) 91% of CO₂ is originated from burning fossil fuels and cement and 9% comes from the different land use strategies. The model is calculating with both of the large emitting factor. In order to mitigate possible impact the model is going to help us to foreseen the future changes under different versions of the base model.

For the sake of simplicity minor events are going to be neglected in the model. For instance the emissions resulting from human activities are not considered as a carbon flow, as it represents only a few percent.

Versions of the base model and results

This section's purpose is to run the base model in Anylogic software, then execute several alterations on parameters and interpret the results. There is going to be one plus three versions. The null version will be the base model created by Hartmut (1994, 2007). The first version is going to modify the future consumption of fossil fuel parameters. The second version will examine different deforestation and afforestation strategies. The third version develops suggestions for energy and forest policies that stabilize CO₂ concentration in the atmosphere.

Null Version



2. Figure Null version output table (the figure is made by the author)

Looking at the base model output table (see Figure 2) it corresponds with the historical trends of carbon increase. The model was run between the period of 1850 and 2052. The atmospheric carbon has increased from 280 ppm to 684 ppm. It is observable on the yellow diagrams (Figure 2) that starting from the equilibrium state carbon begins to increase heavily in the atmosphere due to the logistic curve of fossil fuel carbon emission. The carbon uptake of the biosphere is being negatively affected by the deforestation and net primary production rate relative to the forest area. It results in a negative slope. The rate of respiration is depending on the area of the terrestrial ecosystem. Therefore the respiration rate is going to decrease hence more carbon remains in the atmosphere.

If the model is running until the consumption of fossil fuel saturate at a rate of 15 Gt C, it is going to happen in year 2365. By that time the Carbon in biosphere will settle down at a new equilibrium point. However in contrast the carbon concentration in the air is steadily increasing.

First Version

The first version illustrates the possible outcomes if the decision makers are going to realize the harmful effect of fossil fuels and willing to act towards sustainability. In the model input parameters will be changed around the base model which serves as a reference point to see the change effect on the outcome.

First of all the model parameter, the saturation of fossil fuel consumption, is going to be modified to 5, 10, 15, and 20 GtC/yr at *ceteris paribus*. According to my expectations, the atmosphere carbon content was increasing with a slower rate (see Table 1).

Year	Saturation level (GtC)	Carbon content (ppm)
2052	5	544
2052	10	632
2052	15 base scen.	684
2052	20	726

1. Table Showing carbon content at different saturation levels

If another parameter, growth of fossil fuel consumption will be altered to 0.02, 0.03 and 0.04 % per year at *ceteris paribus*. The comparison table shows the accumulation of carbon concentration in the air, but the growth rate is a stronger influential on carbon emission than saturation in consumption (see Table 2)

Year	Growth rate of FF (pct/yr)	Carbon content (ppm)
2052	0.02	479
2052	0.03 base scen.	632
2052	0.04	913

2. Table Showing carbon content at different growth levels

The best strategy would be if fossil fuels are saturating at a rate of 5 Gt C and there would be a 0.02 growth rate. If it happens, it would result in 455 ppm in 2052 which is still high, but would induce lower emission than currently.

Second Version

The following version is looking at several deforestation strategies. Hypothetically the rate of deforestation will be modified to a better and worse version while the base model will

function as a control output. The rates of cutting trees are going to be 0.15, 0.2 and 0.25 % per year. If the rate of deforestation will be lowered, a slight reduction would be experienced in carbon content (see Table 3)

Year	Rate of deforestation (pct/yr)	Carbon content (ppm)
2052	0.15	661
2052	0.2 <i>base scen.</i>	686
2052	0.25	708

3. Table Showing carbon content at different rate of deforestation

compared to the base model. Cutting more trees out is not an option to consider, but as a worst case version we can see that the carbon content will increase to 708 ppm.

The next step was to alter the end date of deforestation. If decision makers and politicians fail to change their forestry strategy on time and continue with the current rate of environment degradation, it is necessary to understand how much burden it means for the environment. If deforestation stops in 2025, it increases the level of carbon to 691 ppm, which is increasing slowly and constantly as the time is being postponed (see Table 4).

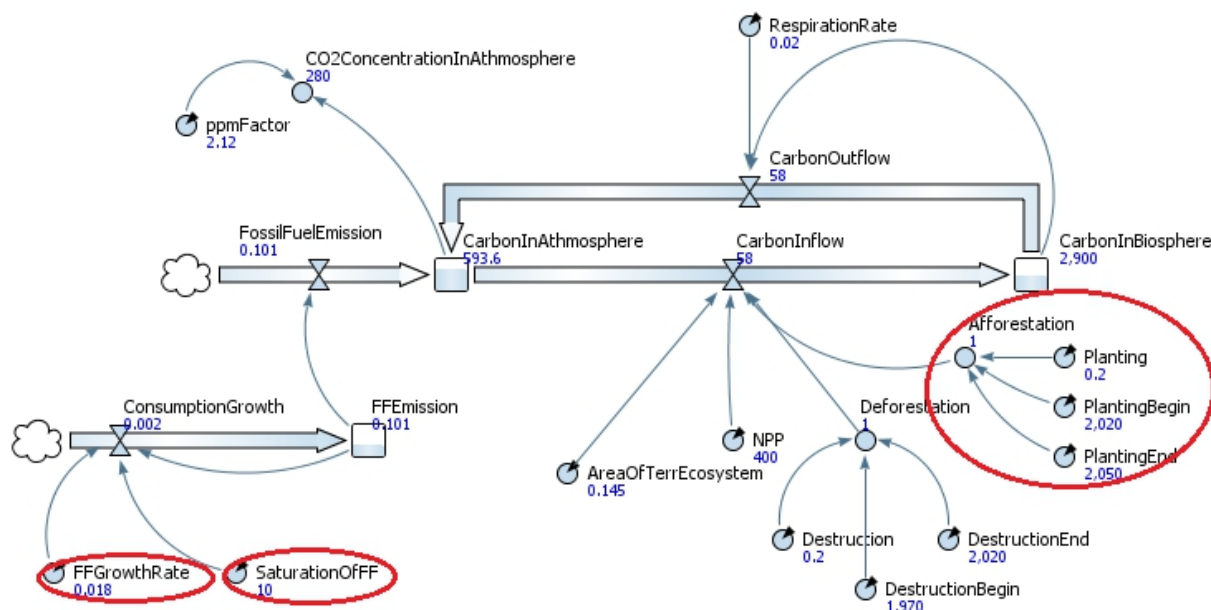
Year	End of deforestation (yr)	Carbon content (ppm)
2052	2020 <i>base scen.</i>	686
2052	2025	691
2052	2030	696

4. Table Showing carbon content at different end of deforestation

It is easy to realize that reducing the volume is more influential, then the end of deforestation. It is also necessary, but results only in a relatively small carbon increase in the atmosphere. Policy makers should go beyond and develop alternative strategies at the meantime to reduce carbon content.

Third Version

The last version is the combination of best practices. A hypothetical energy and forestry strategy is going to be investigated that aims to stabilize carbon dioxide in the atmosphere. First the strategies will be introduced then the outcome will be investigated. The first step would be to regenerate the lost biosphere and start to plant trees. Therefore the afforestation auxiliary was added to the model similar to the deforestation equation (see red circle in Figure 3). It is determined by the level of afforestation (parameter named as 'Planting'), by the beginning and end date of planting trees. As the decision makers will realize the negative effect of destroying forest, will stop cutting out further trees and will start regenerating the lost forest lands. Therefore the model takes 2020 as the year when afforestation starts and 2050 as the end of planting. The rate of afforestation is assumed to be twice as much than the rate of deforestation in order to increase the absorption capacity of the biosphere. It is 0.2% per year.



3. Figure Third version output table (the figure is made by the author)

The other option is to realize a more sustainable energy strategy. It is high time for decision makers to understand the harmful effect of fossil energies on one hand and to believe the finite availability of fossil energies. Energy consumption should be sourced from renewable energy rather than non-renewables. There are numerous alternatives to cover energy needs which are less or non-polluting. For example wind-, solar energy, hydro power plants, bioenergy and geothermal energy are all applicable and developed technologies available on the market. Therefore the growth rate of fossil fuels will be reduced to 0.018% per year, assuming that other non-emitting energy resources will replace the fossil energies. The saturation of consumption in fossil fuel therefore will happen earlier than the base model suggested. Now it is set to 10 Gt C (see red circle in Figure 3).

After running the model several times following different strategies, it was observed that the most effective way to reduce atmospheric carbon is the slower growth rate of fossil fuels. With the above written parameters by 2050 there would be 456 ppm carbon dioxide in the air. The rate of carbon accumulation would be significantly reduced by proper policy making.

Recommendation

The earth has passed in 1988 the safety level of carbon content in the atmosphere neglecting the unforeseen negative consequences. As the human kind severely experiencing global warming, the acidification of ocean, the melting of ice-cap, extinction of species and the frequently occurring natural hazards, they tend to believe it is time to execute changes. These phenomena have impact not just on our natural environment, but also on our economy and society. The economy is spending millions of dollars to correct and revise the traditional way of business models and old polluting technologies. The government is also responsible to insure the society and cover their losses in case of natural hazard and extreme climate events. Huge amount of money is spent on this respect. It is a common interest to warn off fossil fuel resource usage and carbon emission as much as possible. It seems to be plausible, but only with strict policy making. Otherwise if we reduce only a bit of the carbon emission it would still continue heating up (Matthew&Caldeira, 2008, Hansen et al., 2008, Pacauri, Reisinger, 2007).

My recommendation is to act now, as the different versions have illustrated there is a lack of time and increasing carbon dioxide in the atmosphere. The target 450 ppm will be

reached by 2050 in the third version as well, therefore forestry and energy strategy is not remedy for this problem. What has been accumulating since 1850 could not be removed from one day to another from the air. Recommendation is to replace fossil fuel resources with other non-renewable sources at the first place, such as solar, wind, geothermal, hydro, bioenergy...etc. There are some advanced technologies such as the concentrated solar, wave and tidal energy. Try to avoid traditional cars and support electric cars. Proper forestry and agricultural strategy should be favored by decision makers (Matthew&Caldeira, 2008, Hansen et al., 2008, Pacauri, Reisinger, 2007).

Nowadays governments are heavily investing in research and development to find out the best and fastest technology to reduce carbon in the air. It is a highly researched area whether carbon can be artificially drawn from the air. The technology is not there yet to offer a large scale option, but may in the future. There are pilot projects existing at a cost of \$200/tC. To artificially remove 50 ppm carbon from the air would cost around \$20 trillion (Lackner, 2003; Keith, 2006, Hansen et al., 2008). It is a rather capital intensive solution. There is an early application of carbon dioxide capture and storage (CCS) system as well. However afforestation strategy could offer a cheaper and natural way of carbon elimination. As my model illustrated in the second and third versions, this process is able to reduce the carbon content in the atmosphere in a way that the positive effect of carbon sequestration of soil is also increasing. It is being researched that bio-char with another name charcoal would be a potential matter to store carbon for several decades. Bio-char basically is the residue after burning biomass. Usually it is spread on the topsoil as a fertilizer and it generates richer soil content while capturing CO₂. This solution would probably reduce 8 ppm or more in half century (Lehman, 2007; Lehman at al., 2006, Hansen et al., 2008).

Conclusion

The conclusion of the study is that carbon dioxide in the atmosphere is going to exceed the safety zone in the base scenario and go beyond 450 ppm which irreversibly change the ecosystem of the planet where the regeneration of forests for example are not feasible anymore. Trying several versions of the model by following different energy- and agro-strategies, the suitable parameters to reduce carbon are fossil fuel growth rate of 0.018%, saturation of fossil fuel consumption at 10 Gt C, and the afforestation starting at 2020 until 2050 with a rate of 0.2%.

The study covers an important issue of this era. The investigation of carbon dynamics in the atmosphere and the simulation of carbon under different versions attract attention from several researchers. Answering the question in the title – Carbon dynamics: Ever going to stop increasing? – seemingly carbon dioxide is going to accumulate further. However the rate of intensification can be changed by strict policies and with prompt, environmental conscious society the process might even reverse at a given point of time.

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